THE SEDIMENTARY ENVIRONMENT AND GEOLOGICAL EVOLUTION
OF THE
MANITOU PASSAGE AREA OF LAKE MICHIGAN

by
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Professor Jack L. Hough, Chairman
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PREFACE

This study is a part of the geology section of the coherent area study of Lake Michigan of the Great Lakes Research Division, Institute of Science and Technology, University of Michigan. The work was made possible by U. S. Public Health Service grant WP-00311. The coherent area program is under the direction of Professor John C. Ayers, Principal Investigator and Professor David C. Chandler, Project Director.

The first year of this geological study was under the direction of Professor Ayers and the remainder under Professor Jack L. Hough.

During the 1963 season, diving assistance was contributed by Mr. Robert Anderson Jr. and Dr. Wallace P. Wells. Mr. Louis Warnes of Glen Haven kindly contributed storage for the small boat and diving equipment. Mr. Robert Anderson Sr. of Traverse City permitted the writer to make aerial observations and photographs from his airplane.

Field assistance in 1964 was provided by the crew of the R/V NAIAD which included the writer, Lee Somers, Paul Summers, Michael Smith, and John Osterhagen.

The 1964 meter installation was made possible by the excellent cooperation of the U. S. Coast Guard, and especially the personnel of the North Manitou Shoal Light Station, George T. Gautier, Officer in Charge.

The 1963 current meter was constructed with the assistance of the Department of Geology, University of Illinois.

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INTRODUCTION

In 1963 the Great Lakes Research Division began a broadly based study of Lake Michigan. The program includes meteorological, physical, chemical, biological, and geological investigations. The aim of these studies is to observe and interpret the processes in action at present in order to gain some insight into the history of the lake since its formation and its probable future evolution.

The geological portion of this study involves two general types of operation. An extensive survey of the entire lake is being undertaken by means of sediment and bedrock bottom sampling, echo sounding, and continuous seismic profiling of sub-bottom structure. In addition, selected portions of the lake are being subjected to intensive investigation to obtain a better understanding of the details of structure, sediment distribution, and sedimentary environment. The work described here involves one such study made in the Manitou Passage area of the northeastern side of the lake.

The southern half of the shoreline on the east side of the lake is in a comparatively advanced state of development, considering the short span of post-glacial time since the formation of Lake Michigan. The northern part, however, is not as regular and displays the embayed nature of an immature shoreline.

Investigations of the beach sands and offshore sediments of the southern part of the eastern shore are presently being carried out by the University of Illinois, Department of Geology, working in cooperation with the Great Lakes Research Division. These studies are intended to yield information concerning the processes at work along the more maturely developed parts of the shore.

The present work was concerned with the Manitou Passage area of the northern part of the east shore during 1963 and 1964. The Manitou Passage area is located off the northwestern shore of the Lower Peninsula of Michigan between the Leelanau Peninsula and the Manitou Islands. The position 86° W. long., 45° N. lat. is approximately the center of the area.

This study covers only the area lying between the mainland and the southern shores of the islands plus part of the shoal area west of Sleeping Bear Point (figs. 1 and 2). Detailed work was carried out chiefly in the southern part of the passage within a few miles on either side of Sleeping Bear Point.

The area was selected for this study because it is the point where the eastern shore of Lake Michigan changes from a predominantly northerly to a northeasterly trend. This change in direction is accompanied by transition from the relatively regular sand hill bordered shorelines to the south, to an irregular, deeply indented shoreline to the north of the area. In addition, it was known from previous brief visits to the area that the currents are active and that the bottom topography warranted investigation. Furthermore, there are no large settlements, shoreline improvements, or dredged channels in the area. It is essentially in its natural state, unmodified by man..

Insofar as it has been possible to determine, there have been no previous underwater investigations in the area, except for U. S. Lake Survey soundings. There is a map of the glacial geology of Leelanau County (Kelley, 1957), and investigations have been made of the Glen Lake-Sleeping Bear Bay embayment (Johnson, 1958) and of Sleeping Bear Hill (Gillis and Bakeman, 1963).

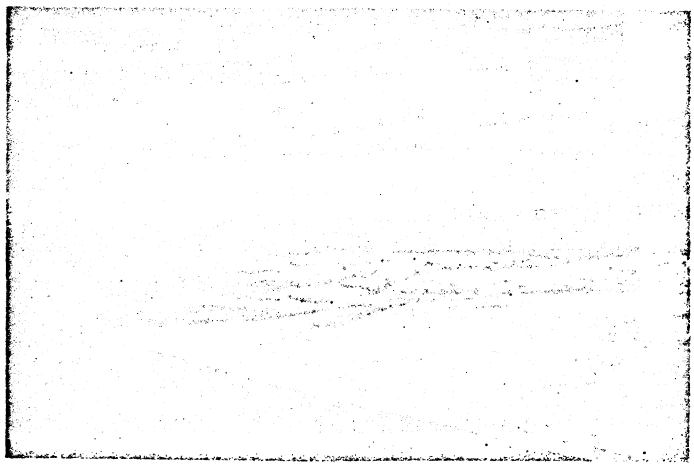

Figure 1   Sleeping Bear Hill and Sleeping Bear Point

Pyramid Point is in the right background and North Manitou Island in the left background. The 1963 meter site is in the lower left corner of the picture.

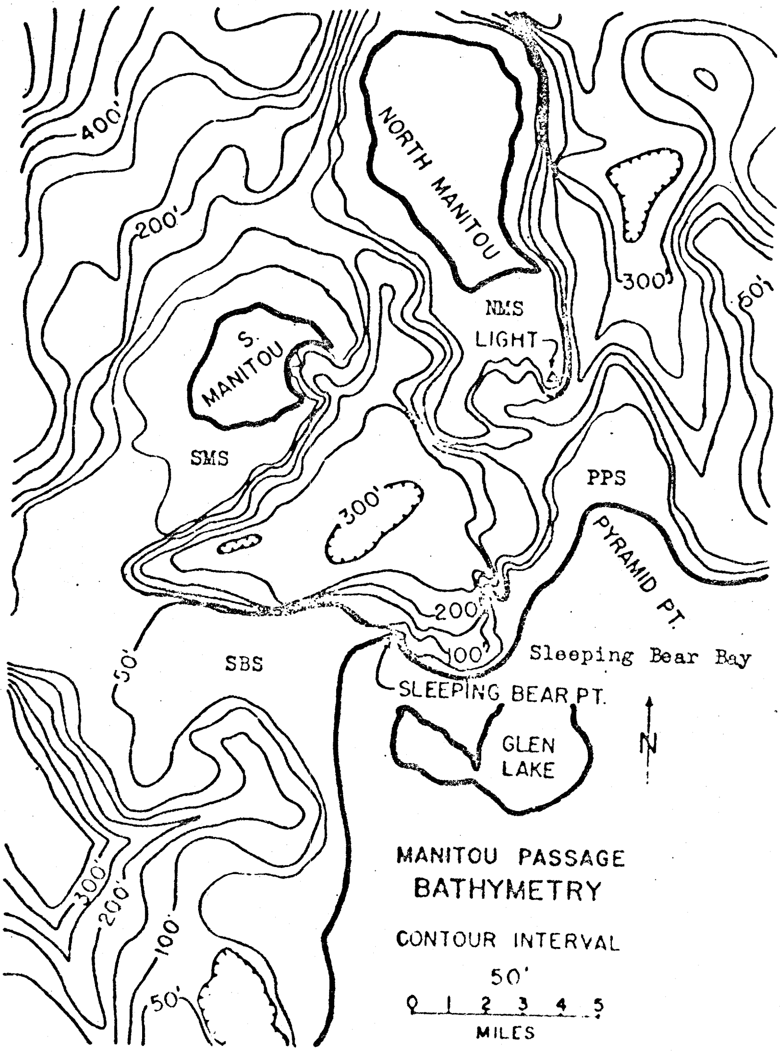

Figure 2 General Bathymetry of Manitou Passage

The abbreviations used are; NMS-North Manitou Shoal, SMS-South Manitou Shoal, SBS-Sleeping Bear Shoal, and PPS-Pyramid Point Shoal.

The Manitou Passage investigation was undertaken with the object of gaining some idea of the magnitude of the forces and processes which determine the sedimentary environment and the meteorological regime which powers it. Three major objectives were proposed. First, it would be necessary to ascertain the wind regime of the area. Since there are no nearby weather stations this was first attempted through use of the wind observations of the North Manitou Shoal Light Station of the U. S. Coast Guard. However, observations are taken only at four hour intervals and installation of a continuous wind recording system was seen to be a necessity. The second and third objects of the study were the measurement of the near bottom currents of the area and the relation of sediment distribution to these currents.

The major part of the sedimentary activity would be expected to take place when the most intense current and wave action occur, and these severe times are precisely those when research vessels and divers are unable to operate. It was necessary, therefore, to locate a current meter on the bottom in order to obtain records affording continuity and measurements of currents under extreme conditions.

No available current meters were suited to this type of installation, and it was necessary to design and construct one to meet the requirements of this study. Since only one current meter could be constructed, it was impossible to measure the over all current pattern of the area.

A further purpose of this investigation was to devise, perfect, and employ direct observation methods of underwater investigation. The use of SCUBA (self-contained underwater breathing apparatus) diving techniques in particular, permits direct observation of sedimentary conditions on the bottom and truly representative sampling of the

sediments. It also makes possible the observation of the small scale configuration of the bottom and the condition of objects lying on the bottom. The diver has somewhat the same comprehension of the nature of the sample area as does the land geologist. However, the diver is greatly limited by the fact that his visibility is very restricted and affords no over-all view of his area. There are also limitations on the number of dives which can be made in a day and the length of time which can be spent on the bottom during deep dives.

During the summer of 1963 most of the work consisted of field investigation of the lake bottom using SCUBA gear. The writer with one or more diving companions made a number of dives in the Sleeping Bear Bay and Sleeping Bear Shoal areas. Some of the dives in the bay were made directly from the shore. Otherwise a small boat equipped with an outboard motor was launched from shore in the bay and used to transport the divers to the diving site. Most of the information gained from these dives consisted of observations which were recorded in a waterproof notebook and some underwater photographs. For bottom sample collection, placement of the current meter and taking echo sounding profiles, the R/V NAIAD made three short trips to the passage from her base in Grand Traverse Bay. The small boat was employed to recover the current meter on 25 October.

For the 1964 season the NAIAD was assigned to the Manitou Passage study on a nearly full time basis. Operations were based at Charlevoix under the direction of the writer. Cruises with a planned duration of 4-5 days were made to the passage. Unfortunately the distance from Charlevoix to the passage necessitated long runs to and from the working area which, combined with the unexpectedly severe weather commonly found in the area, severely hampered operations. As a result complete

coverage of the passage area was not possible.

Diving, echo sounding, and sample collections for the 1964 season were performed from the NAIAD. The continuous seismic profiles were made from the R/V INLAND SEAS which also took some bottom samples and recovered the current meter on 5 November.

The data obtained during the two years of the investigation is on file at the Great Lakes Research Division. Selected portions of it are presented in this paper. A short paper based on some of the 1963 data was presented by the writer (French, 1964).

GEOLOGICAL SETTING

Topography

The shoal areas show remarkable uniformity of depth and bottom character. They are flat and their surfaces are essentially level throughout their extent. Surface relief is only a few feet over the entire shoal with no abrupt changes in level. Depths range from about 30 feet at the outer edge of the most exposed areas (Sleeping Bear Shoal and South Manitou Shoal) to around 15 feet at the landward edges of North Manitou Shoal and Pyramid Point Shoal.

Except for the connecting sill between Sleeping Bear Shoal and South Manitou Shoal, the margins of all the shoal areas are marked by abrupt dropoffs to depths of at least 100 feet. Where these slopes were examined by divers, they consisted of sand resting at, or close to, the angle of repose.

The surface of each of the shoals rises gently towards land to a point a few hundred feet from shore, then slopes with a somewhat higher gradient up to the shoreline. In all cases, the shoals adjoin shorelines, which have bluffs over 100 feet high.

Sleeping Bear Shoal which was the most intensively studied, appears to have two dominant bottom sediment types. The very center of the shoal is covered by a continuous pavement of cobbles, small boulders and pebbles. Diver examination shows that the pavement is essentially one cobble thick (about 20 cm). The material below this cobble is reddish brown sand (Munsell designation 10R 4/4 wet, 10R 6/4 dry) containing about 10 percent fines. The material is quite firm in place and was described in field notes as a firm sandy clay because the diver had to use a knife blade to dig out a sample (sample 032, appendix). Subsequent analysis, however, showed the material to be a fairly well-sorted medium sand containing a few granules and small pebbles, and only 10 percent fines. It should be noted that this material is substantially identical to that which is obtained by digging into the face of the bluff on the west slope of Sleeping Bear Hill. The firmness of the material in place suggests that it is highly compacted and is the sandy till which composed the original, post-glacial, topography of the area.

Away from its center the remainder of the top of Sleeping Bear Shoal is covered by very uniform, well-sorted, medium sand. Attempts to dig through this cover of sand were unsuccessful so it must be at least several feet thick.

The surface of the sand is covered by sharp-crested symmetrical ripple marks (fig. 3) about 20 cm apart. The crests of the ripple marks stand about 4 cm high. The marks are, in general, parallel to the

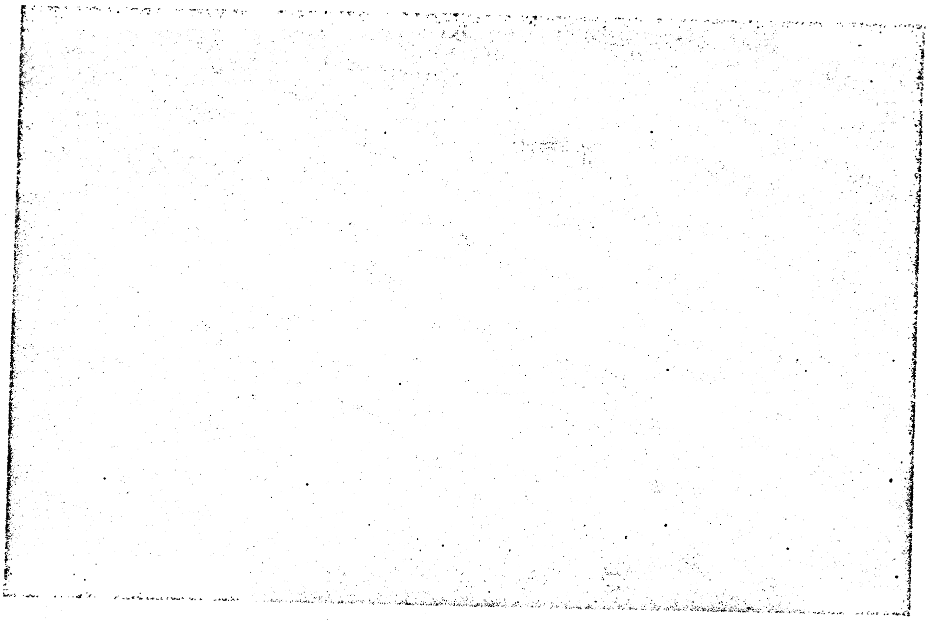

Figure 3 Ripple marks on Sleeping Bear Shoal

Distance between crests about 20 cm.

crest-lines of the large surface water waves which were last active in the area. After a strong southwest wind which produced large waves, the crests of the ripple marks trend northwest-southeast, while after a northwest blow, the ripple marks trend northeast-southwest. Within a few hundred feet of the shoreline, the ripple marks always parallel the shore.

Observations were also made on the southern part of North Manitou Shoal in the vicinity of North Manitou Shoal Light Station where the current recording apparatus was placed during 1964. Conditions here are more vigorous than those found on Sleeping Bear Shoal. The sand here is medium-coarse with frequent pebbles. As can be seen in figure 4 the surface of the sand is quite irregular with no strong development of ripple marks.

Diver observations were made in a depth of about 20 feet at the 1963 current meter site on Sleeping Bear Shoal (fig. 5). The sand here is medium-fine and conditions can be considered as fairly typical of the sandy parts of the shoal in general.

These observations consisted chiefly of measurement of the current flow immediately above the bottom by observing the movement of small puffs of dye. A very small amount of Rhodamine-B dye was ejected from the end of a capillary tube which was positioned either just below the surface of the sand or somewhat above it. The movement of the dye puff along a measured distance on the bottom was timed and the outline of the puff sketched at intervals after the original introduction.

Dye which was injected just above the surface of the sand moved off down-current with an oscillatory motion. These oscillations had the same timing as the passage of the surface water waves that existed at the time. The length of each current oscillation was about the same

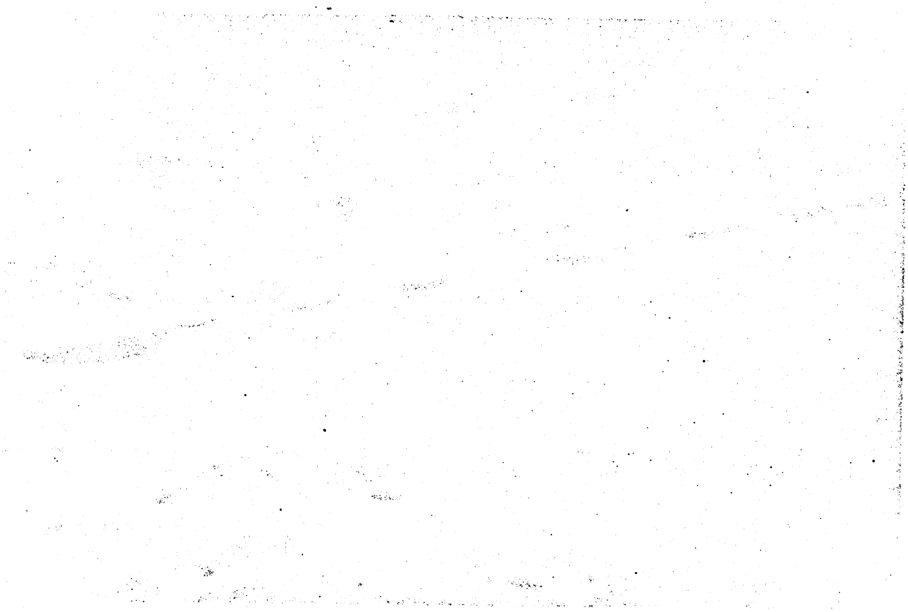

Figure 4 Irregular bottom on North Manitou Shoal

Underwater telephone cable in center of picture is about 8 cm in diameter.

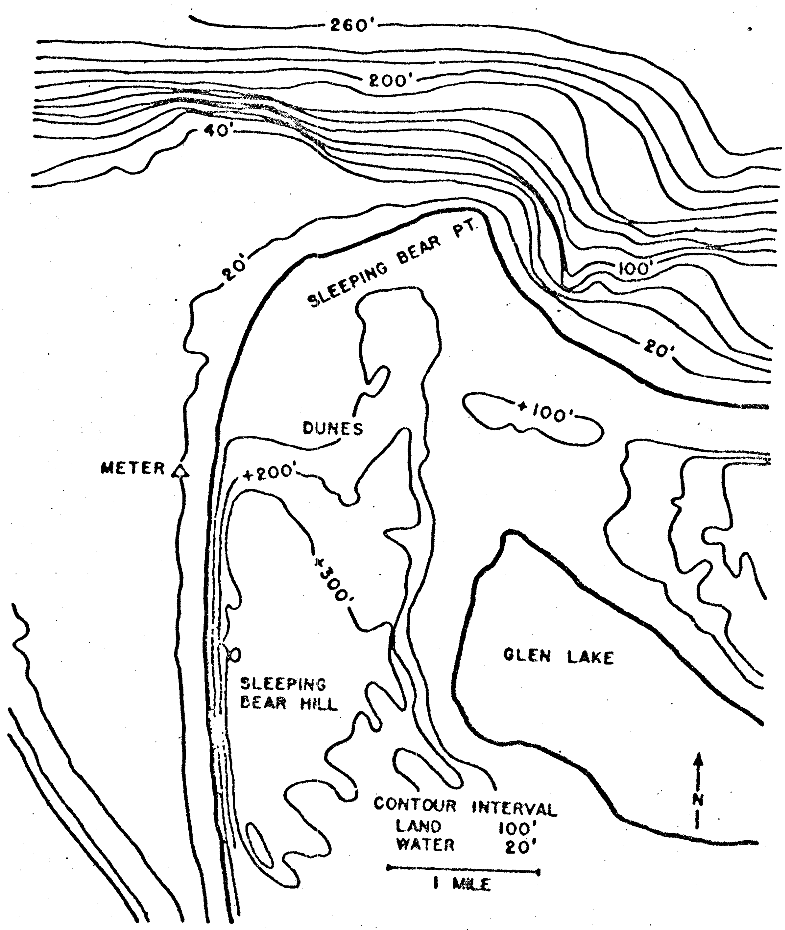

Figure 5 Vicinity of Sleeping Bear Point

Location of 1963 current meter installation is shown.

as the distance between the crests of the ripple marks. Dye which was injected into the sand appeared at the surface intermittently and emerged with a similar oscillating movement, indicating that the interstitial water of the sediments was participating in the movement of the bottom water.

Superimposed on this oscillatory motion was a general drift which was always at a considerable angle to the direction of the oscillations. The net movement of the dye puff was, therefore, in the form of a flattened spiral the long axis of which was almost parallel to the crestlines of the ripple marks.

Dye puffs ejected 50 cm above the bottom had a considerably greater amplitude of oscillation with a less flattened trajectory and moved off with the general drift of the water at a significantly greater velocity than puffs released nearer the bottom. Figure 6 shows the outline of a dye puff 30 seconds after it was (A) injected just below the surface of the sand at point O; (B) injected 3 cm above the surface of the sand at point O; and (C) injected 50 cm above the bottom at point O. This 30 second period of observation effectively eliminates the effect of the current oscillation and only shows the general drift of the water mass. The lack of a tail on puff (C) clearly shows that the zone of maximum shear occurs within about 40 cm of the bottom.

The fact that the interstitial water of the sediment takes part in the near-bottom oscillatory current would seem to indicate that the surface layer of sand on the bottom would be subject to a lifting motion during part of the time and would more easily be placed in suspension than might be assumed from simple consideration of the shear forces acting on an impermeable bottom.

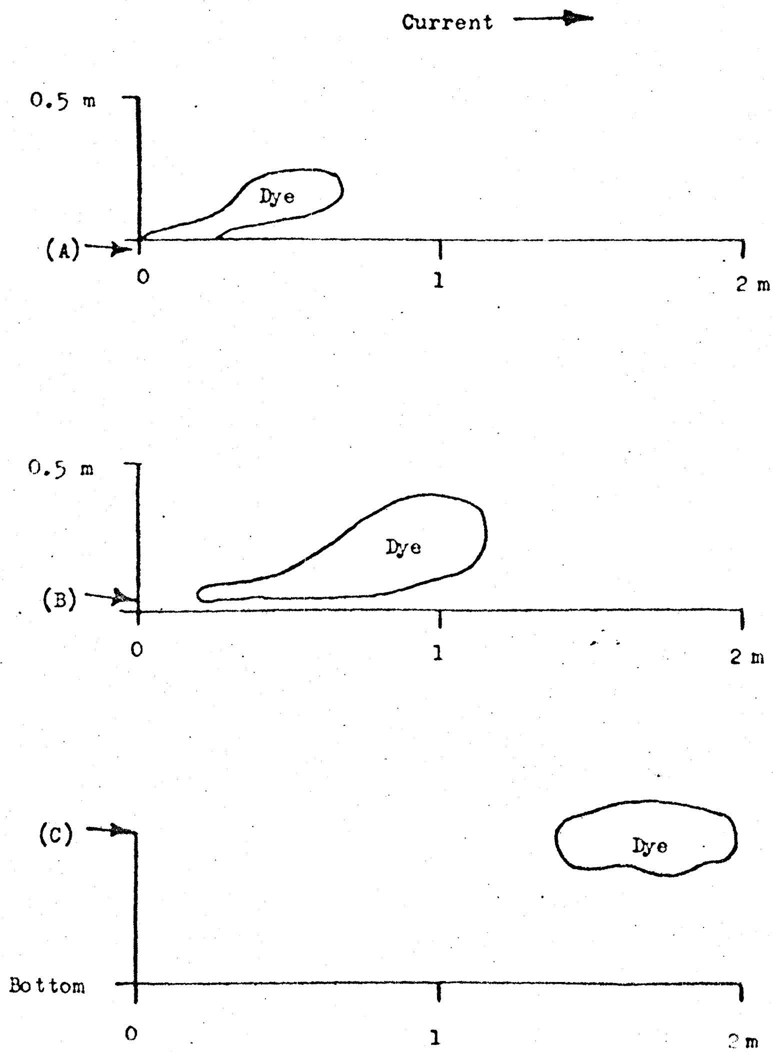

Figure 6 Near-bottom current studies

These observations could be made only during relatively mild conditions. Winds were generally force 3 (12 mph) or less with waves less than 0.5 m high. The surface current under these conditions was generally about 15 cm/sec and near bottom currents on the order of 5 cm/sec. Conditions this mild existed only about 40% of the time during the relatively calm month of August, with velocities five times as great existing 20% of the time. Conditions at this site during the much more windy time of fall and winter can only be surmised; wave motion must be on a much larger scale at such times.

The edges of the shoal areas are terminated very abruptly by a sharp increase in gradient. Within a horizontal distance of a few feet the level bottom changes to a slope of 30° - 40°. This steep slope usually descends smoothly to a depth of somewhat over 100 feet. From this depth a less regular slope extends to the floor of the adjoining basin.

It was possible to examine only the upper 100 feet of the slope by diving. This part of the bottom consists of medium-fine sand with up to 15% silt, laid down with a very smooth firm surface. This surface has a pattern of ridges on it which trend directly down slope. Near the top of the slope, these ridges are about 10 cm high and 50 cm crest-to-crest (fig. 7). Further down the slope in a depth of 70 feet they become larger with crests about a meter high spaced several meters apart. It was not possible to observe whether or not the smaller ridges were continuous with the larger ones. The ridges do not resemble ripple marks in that they were not observed to either branch or terminate. Their profile is symmetrical but the ridges are not sharp-crested. The ridges appear to have the same degree of roundness as the troughs between them. Another reason for doubting that these ridges are true

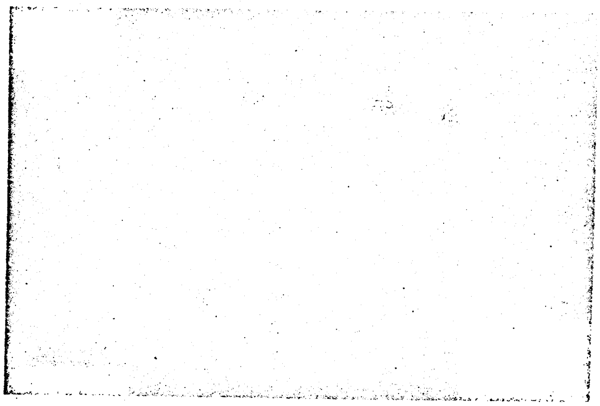

Figure 7   Ridges on north slope of Sleeping Bear Shoal

ripple marks is that near the top of the slope the ridges trend nearly at right angles to the conventional sharp-crested ripple marks found on the edge of the shoal only a few feet away. Possibly these ridges are something similar to the sand waves which are observed to form in streams and channels which have very high current velocities. This would require occasional high velocity currents moving along the slope in an easterly or westerly direction.

In a depth of about 100 feet near the base of the steepest part of the slope, hewn timbers were observed projecting from the bottom. Probings around these timbers, which appear to be parts of wooden ships, showed that they are embedded several feet into the bottom. Assuming a maximum credible age for the timbers of less than 200 years, the sedimentation rate must be at least two feet per century. Compared with nearby submerged pilings of known age, it would appear that the wood is probably less than 50 years old, yielding a proportionally greater sedimentation rate.

It was not possible to observe the currents on the slopes as carefully as those on the shoals. It was seen, however, that the current which had come across the shoal did not follow the slope downward but flowed horizontally out above the slope. Indeed, under these conditions, a slight current was observed to run up the slope in a direction opposite to the main current coming off the shoal. This might represent an eddy current powered by the jet effect of the main current where it separates from the lake bottom at the top of the slope. These minor upslope currents were generally less than 5 cm/sec.

Sleeping Bear Bay and South Manitou Island Harbor are the only places in the passage where the land adjoins deep water without an

intervening shoal. The western part of Sleeping Bear Bay was examined in detail by divers (fig. 5).

In the southern and western part of the bay there is a narrow band of shallow water paralleling the shore. This extends to a depth of 15-20 feet and is generally less than 100 feet wide. At the outer edge of this shallow area there is an abrupt increase in the slope of the bottom similar to that at the edge of the shoal areas. This slope extends to a depth of 30-40 feet at essentially the angle of repose. Although the angle of the slope was not accurately measured, it is considered to be at the angle of repose because of the fact that any effort, by a diver, to dig into the face of the slope caused the entire area of the slope above the point of digging to slump and slide downward. The face of the slope is very smooth and free from vegetation. The sand of this slope is essentially identical to that of the slopes bordering the shoal areas, having up to 15% silt and having a smooth firm surface.

From the base of this slope, the bottom drops at a lesser gradient outward to the deep central part of the passage.

At the base of the steep slope the bottom is covered by a system of parallel ridges trending roughly northeast-southwest. Vegetation which is identified as algae of the family Characeae grows on the present crests of the ridges. The ridges are about 40 cm apart and rise 5 cm above the intervening troughs which are completely free of algae. The algae forms a dense mat of intertwined filaments which rise about 10 cm above the surface of the sand. Remains of these filaments can be traced downward a considerable distance into the sand. It appears that this mat of filaments would be a very effective sediment

trap since any sand which might settle into it would be very unlikely to be re-eroded. Possibly the algae originally established itself in the hollows between the ridges (where an accumulation of organic material is found) and by causing preferential deposition brought about an inversion of topography to the present state. The ridges are observed to run under the base of the steep slope which is apparently encroaching on the area.

Outward from a depth of about 50 feet the vegetative cover becomes a continuous mat of filamentous algae and no marked ridge system is found.

In this area, at a depth of about 45 feet, a partially buried anchor was found. The anchor was recovered and it is estimated that it had been covered by about 1.5 feet of sand since it was emplaced. Local inquiry established that this anchor is probably one which was used for shifting lumber ships prior to World War I. This would imply a present sedimentation rate of 2-3 feet per century.

The deep central basin of Manitou Passage is the roughly triangular area bounded by the 250 foot depth contour, situated between Sleeping Bear Bay and South Manitou Island (fig. 2). It was not possible to examine the bottom at this depth by either diving or photography.

The floor of the basin slopes gently from a general depth of about 280 feet around its periphery to the center where the depth just exceeds 310 feet. Sediment samples taken in the southeastern part of the basin show that the bottom material is quite uniformly a silt which contains about 25% sand and less than 5% clay.

Sub-Bottom Geology

In the southern part of the area several traverses were made with a Continuous Seismic Profiler or "Sparker." Figure 8 is an isometric fence diagram of these profiles. In plotting these profiles no correction was made for an increase of sound velocity in the sediments, because it is believed that the sonic velocity of lightly compacted sediments is not very much greater than that of the water. The profiles show the relative position and approximate depth of the sub-bottom horizons.

The Sleeping Bear Shoal profile R-Y and most of Y-Z has essentially no sub-bottom detail. The tentative horizons shown may well represent spurious multiple echos of the bottom, and in any case are not very extensive. There is a strong sub-bottom horizon under the northern slope of the shoal, however, which is generally steeper than the present lake bottom and appears to be truncated by the top surface of the shoal. This horizon appears to be continuous with one in the deep basin of Manitou Passage at a depth of about 100 feet below the present lake bottom. The continuity of this horizon suggests that it might be the original post-glacial surface of the passage area.

Section L-K which passes close to the tip of Sleeping Bear Point suggests that the point is essentially a pile of sand which is being built out over the pre-existing lake bottom. The southeasterly parts of sections L-K and J-K show that within Sleeping Bear Bay, there is a tendency to smooth the topography by truncating hills and filling hollows.

Under the essentially level part of the floor of the deep basin (depths greater than 280 feet) there is a persistent horizon 20-40 feet below the present bottom. This pinches out around the edges of

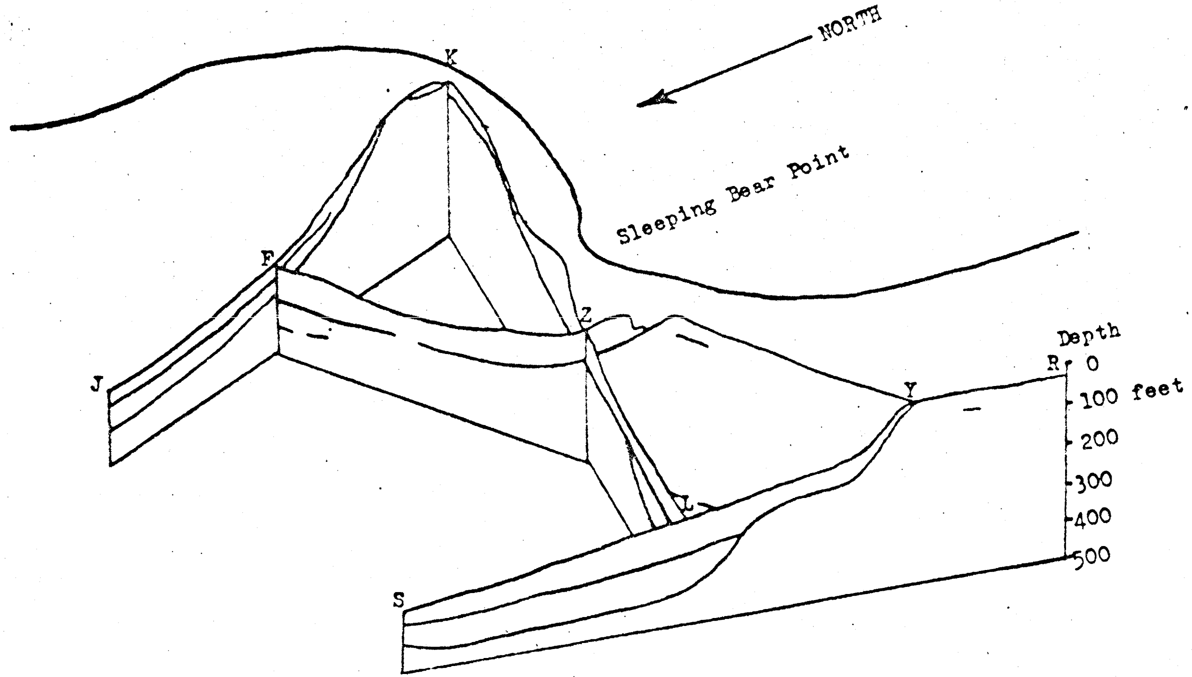

Figure 8 Fence diagram of Sub-bottom horizons

the basin and evidently indicates some change or hiatus in the sedimentary filling of the basin. It may well represent the Chippewa low stage when the passage probably contained a lake separate from the main body of Lake Chippewa (Hough, 1955).

Sediment Distribution

Bottom samples were taken at the points shown in figure 9. The samples were taken either with an Orange Peel Dredge lowered from the NAIAD or INLAND SEAS or by a diver scooping a sample with a trowel. In either case the sample is representative of the top few inches of the sediment.

The sediment samples were analyzed for particle size distribution by a combination of sieving and hydrometer methods. Sand and granule sizes were sieved using the Tyler Standard $\sqrt{2}$ series shaken by a RoTap Automatic Shaking machine as described by Krumbein and Pettijohn (1938, p 138). Analysis for the silt and clay sizes was made by the Bouyoucos hydrometer method as modified by the American Society for Testing Materials (1950). If pebbles were found in a sample their presence was noted but no attempt at quantitative description of the pebble sizes was made. A cumulative curve was plotted and statistical measures were calculated for each sample using the phi notation of Inman (1952). A tabulation of these measures is given in the appendix.

Figure 10 is an isopleth plot of the phi median particle diameters of the sediments. The shaded areas represent bottom material composed of cobbles and boulders and are considered to be areas of non-deposition.

The sands of the area are composed dominantly of quartz, with

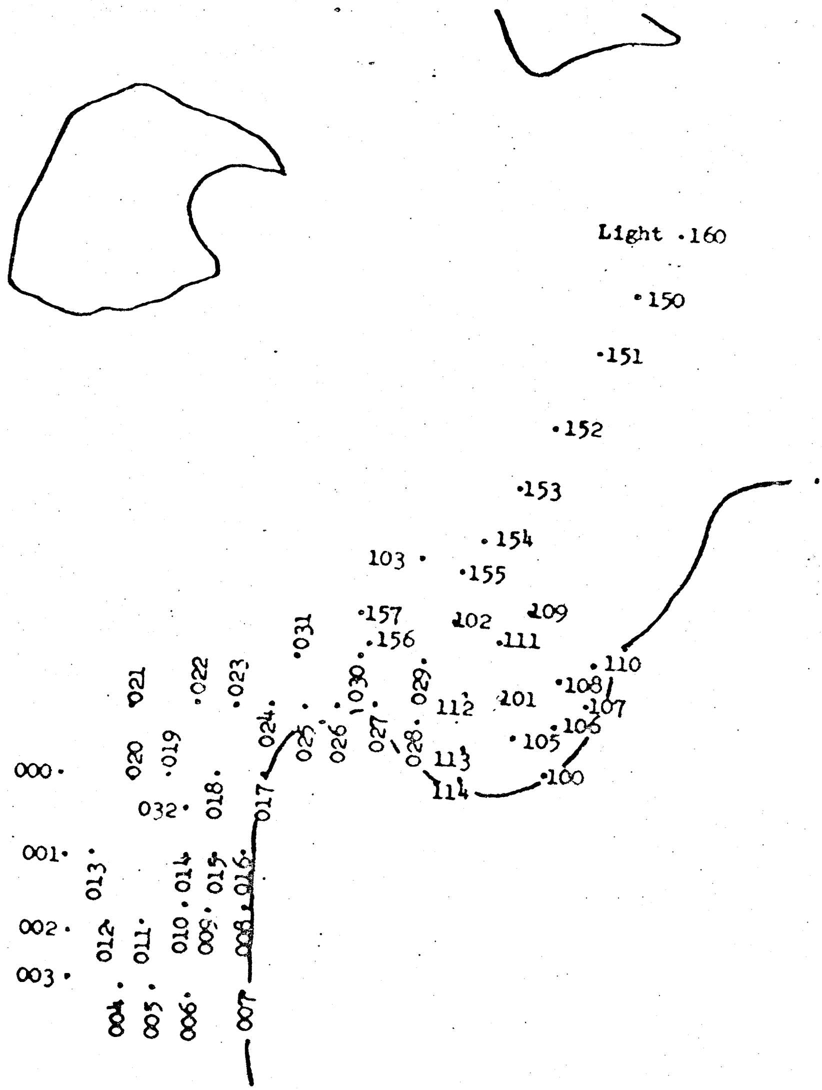

Figure 9 Location of sediment samples

Figure 10 Phi Median distribution

feldspars and various heavier minerals making up the remainders. They are typical of sediments derived from the glacial drift.

Except at its center Sleeping Bear Shoal is seen to be covered by a rather uniform medium sand with a strip of fine sand along the shore of Sleeping Bear Hill. The sediment on the slopes both north and south of the shoal is fine sand containing up to 15% silt.

A band of medium sand extends around the tip of Sleeping Bear Point and along the south shore of Sleeping Bear Bay. The remainder of the bay, except for the cobble area on the east side, contains fine and very fine sand with increasing silt content northward.

The floor of the central basin is covered with a medium silt which contains about 25% sand and less than 5% clay. The single line of samples which extends from the central basin northeast to North Manitou Shoal Light shows an abrupt change from the silt of the basin to a medium sand. The sand in the deep channel between Pyramid Point and North Manitou Island is coarse and contains less silt than the sand at corresponding depths in the Sleeping Bear Point area. The single sample of sand on the top of North Manitou Shoal is somewhat coarser than any found on Sleeping Bear Shoal.

Phi deviation is a general measure of the degree to which a sediment is sorted. The numerical value of the deviation becomes smaller with progressively greater degrees of sorting. Figure 11 is an isopleth plot of the deviation of the sediment samples.

The sand on the shoal areas is seen to be quite well sorted and that of the slope areas somewhat less so. It is significant to note that the most poorly sorted material is found on and near the base of the slope off the tip of Sleeping Bear Point. This is probably partially due to the addition of wind-blown sand which was observed to be carried out to that area.

Figure 11 Phi Deviation distribution

CURRENTS

Sleeping Bear Shoal

The current meter developed for these investigations has a sensing unit which consists of a pendulum suspended from the apex of a tripod by means of a universal joint. At the lower end of the pendulum there is a high-drag configuration consisting of a vertical cylinder 11 inches in diameter by 10 inches high, open at both ends. It is deflected from the vertical in the direction of current movement. The amount of deflection is a function of the current velocity. The orientation of the pendulum is sensed by mercury switches contained in its upper end. The switches are connected via a flexible multi-conductor cable to a recording unit. For the 1963 installation, the recording unit was battery operated and housed in a watertight container placed on the lake bottom near the tripod. This unit made a spot recording of the current direction and velocity range every 20 minutes by discharging capacitors through a strip of electrically sensitive paper.

The meter was calibrated in the tow tank facility of the Department of Naval Architecture and Marine Engineering at the University of Michigan. The velocity magnitudes recorded by this model were: 1, 8-15 cm/sec; 2, 15-23 cm/sec; and 3, over 23 cm/sec.

Since the drag portion of the pendulum covers a considerable vertical interval which is directly in the zone of maximum current shear, these velocity magnitudes can only be considered to be approximations of the general water movement near the bottom.

The meter was placed in 20 feet of water about 1200 feet off the west face of Sleeping Bear Hill (fig. 5).

Unfortunately, a progressive malfunction of the paper advancing mechanism led to an increasing irregularity of event timing and finally complete failure after about two months of operation. For the first month of record, however, it was possible to record observations representing about 95% of the elapsed time. Even though the time of each observation could not be established except at the beginning and at each time the chart paper was changed, it was at least possible to record the frequency of occurrence of the various current directions and velocity ranges. The period of good record extends from 1200, 8 August when the meter was first emplaced until 1600, 4 September 1963 when the chart paper was changed.

This period appears to be representative of almost the entire range of current velocities since it includes both calm periods and a severe storm which occurred on 12, 13, and 14 August with sustained winds of over 50 mph. Unfortunately the current velocity for much of this period exceeded the highest range of the meter so that the true maximum velocity is not known. Only the most severe late fall storms would be expected to produce more rigorous conditions.

Table 1 lists the frequencies of the various currents at this point and figure 12 is a rose showing this same information. Note that the currents are named according to direction <u>toward</u> which they flow.

It is readily apparent that the current flow is almost all directed north and northwestward. This can be most readily explained by considering the proximity of the shoreline to the east of the meter site. While working at the site, divers noted that the surface currents under

Direction of Current Flow

	NE	E	SE	S	SW	W	NW	N	totals
8-15 cm/sec						2.5	8.5	19.5	30.5
15-23 " "	1.0			0.5	2.5	3.0	6.5	27.0	40.5
23 " "	0.5				8.5	3.5	5.0	2.5	20.0
totals	1.5			0.5	11.0	9.0	20.0	49.0	

Periods of little or no current 8.5

Table 1 Current Frequency of Sleeping Bear Shoal
8 August through 4 September 1963

Expressed as percentage of the total observations that the current flowed toward the direction indicated.

the prevailing southwesterly winds were generally flowing shoreward while the bottom currents at the same time flowed northward and northwestward in an offshore direction. This could be explained by assuming the existence of a set-up of the lake surface against the shoreline with consequent secondary currents flowing down the gradient of the set-up and being deflected to the right by Coriolis force. This general process is described by Ayers (1962).

North Manitou Shoal

Since the results of the 1963 current measurements made it appear desirable that a better time relationship between winds and currents be established, the current meter location was moved in 1964 from the open lake off Sleeping Bear Hill to the vicinity of the North Manitou Shoal Light Station (marked 'Light' on figure 2). At this location

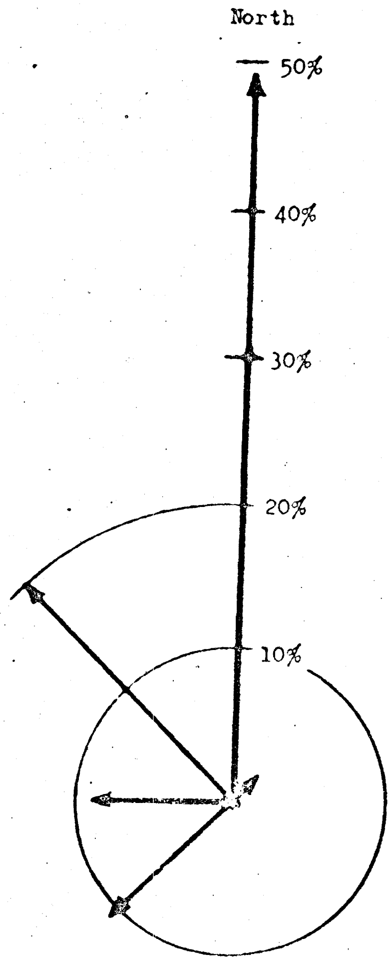

Figure 12 Current rose for Sleeping Bear Shoal
8 August through 4 September 1963

wind direction and velocity were sensed by a wind vane and anemometer mounted on the top of the light structure about 100 feet above the water surface. The sensors were connected to a recording mechanism, located in the living quarters of the light station, which was tended by the U. S. Coast Guard personnel who manned the station. The current meter was placed 400 feet north of the light structure and connected to the same recorder by cable (fig. 13).

Unfortunately the limited availability of multi-conductor cable at that time made it necessary to restrict the reporting of currents to four velocity ranges and only two directions. The record obtained yielded hourly summaries of the following: wind direction, average velocity of the wind (recorded in mph and converted into Beaufort force), general current direction (eastward and westward), and approximate magnitude of the current velocity.

For the 1964 season, the high drag configuration on the pendulum was redesigned in order to decrease the sensitivity of the meter. The new configuration was in the form of a rhombic dodecahedron about 10 inches across. Recalibration in the university tow tank facility yielded the following current velocity magnitudes: 1, 25-40 cm/sec; 2, 40-50 cm/sec; 3, 50-75 cm/sec; and 4, greater than 75 cm/sec.

Wind records were obtained starting 2300, 5 May through 1600, 5 November 1964 for a total of 4409 hourly observations. The recording system was not operating for a total of 82 hours of this time. The wind record is, therefore, 98.1% complete. The current meter was placed in operation at 2100, 30 July and operated until it was overturned by wave action during a storm at 1800, 26 September 1964. This period totals 1387 hours and the combined wind-current record is 97.2% complete.

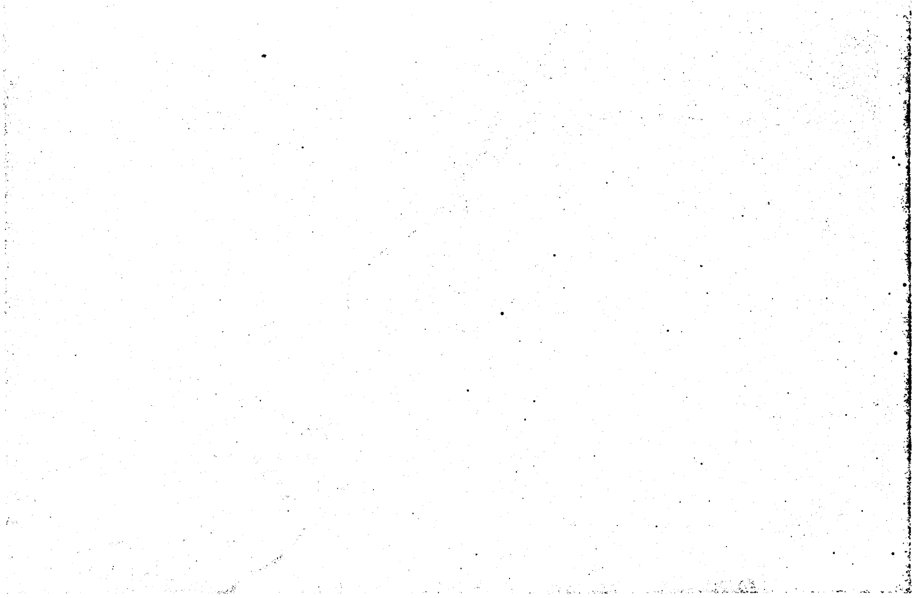

Figure 13 Current Meter in place on North Manitou Shoal

The initial step in analyzing this information was to determine the frequency of occurrence of the various wind directions and velocity ranges for the entire period of wind record. In order to simplify analysis the wind velocities were grouped into three ranges: Mild winds, force 1-3, 1-12 mph; Strong winds, force 4-6, 13-31 mph; and Gale winds, force 7-9, 32-54 mph. This grouping has a practical significance for this study because, in general, it was only possible to make collections and current observations during periods of mild winds. The information is presented as table 2 and figure 14. Note that the winds are named according to the direction from which they blow.

The salient characteristic of the wind pattern is seen to be that whereas there is no dominant direction for mild winds, there is a great predominance of strong and gale winds from the southwest.

In the same manner, a wind frequency tabulation was made for approximately the same period as the available current record. The

Wind Direction

	NE	E	SE	S	SW	W	NW	N	totals
1-12 mph	6.0	3.9	6.1	3.5	5.2	5.0	4.9	5.1	39.8
13-31 mph	2.3	0.9	1.7	8.1	22.1	5.2	6.9	7.2	54.5
32-54 mph			1.3	3.3	0.7	0.4			5.8
totals	8.4	4.9	7.8	12.9	30.6	10.9	12.2	12.3	

Table 2 Wind frequency at North Manitou Shoal
5 May through 5 November 1964

Expressed as percentage of the total observations that the wind blew from the direction indicated.

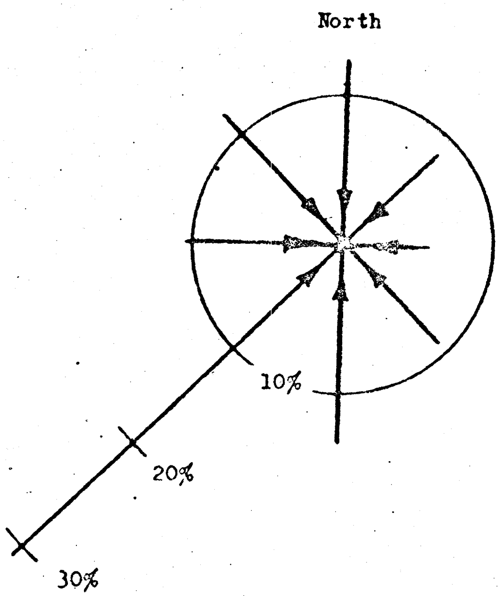

Figure 14 Wind Rose for North Manitou Shoal
5 May through 5 November 1964

tabulation covers the period 26 July through 26 September 1964 (table 3, figure 15). There is no substantial difference between the wind regimes of the two month period and the entire six month period. During the period of wind and current record, the wind through the passage blew from the westerly quadrant 55% of the time and from the easterly quadrant 21% of the time.

Since it was only possible to record the current data on a basis of a generally eastward or generally westward flow, the frequency of the various current directions and velocities can be depicted as a simple bar histogram (fig. 16, table 4).

The hourly plot of winds and currents shows that the current generally flows toward the direction from which the wind is blowing.

It is immediately apparent that there is a major difference between the wind and current regimes. The current flows toward the west 54% of the time which is almost exactly the time fraction during

	Wind Direction								
	NE	E	SE	S	SW	W	NW	N	totals
1-12 mph	5.6	3.5	7.8	3.1	5.2	6.3	5.5	4.0	41.0
13-31 mph	2.2	2.0	2.2	8.8	19.0	8.3	8.5	4.4	55.5
32-54 mph		0.1		1.3	1.5	0.6			3.5
totals	7.9	5.6	10.0	13.2	25.7	15.1	14.0	8.4	

Table 3 Wind frequency at North Manitou Shoal
20 July through 26 September 1964

Expressed as percentage of the total observations that the wind blew from the direction indicated.

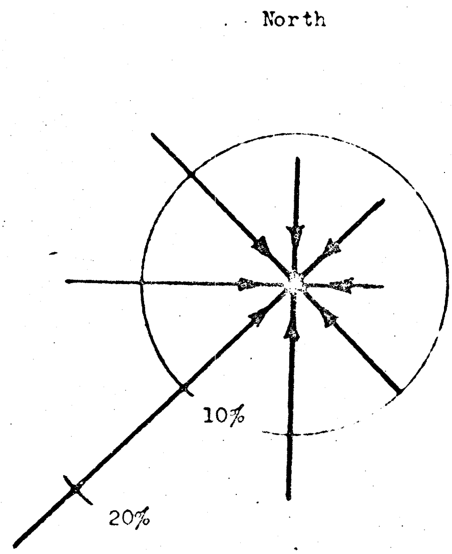

Figure 15 Wind rose for North Manitou Shoal
26 July through 26 September 1964

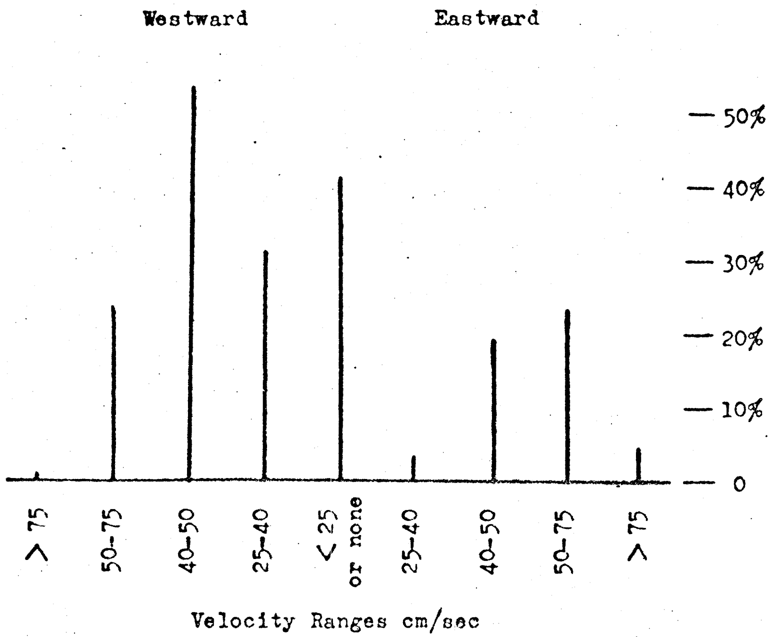

Figure 16 Current frequency histogram for North Manitou Shoal 30 July through 26 September 1964

	General Current Direction		
	Westward	Eastward	totals
25-40 cm/sec	15.4	1.9	17.3
40-50 cm/sec	26.7	9.6	36.3
50-75 cm/sec	11.9	11.8	23.7
75 cm/sec	0.1	2.2	2.3
totals	54.1	25.5	
	Periods of little or no current		20.5

Table 4 Current at North Manitou Shoal
30 July through 26 September, 1964.

Expressed as percentage of the total observations that the current flowed toward the direction indicated.

which the wind blows from the west. Likewise, the time fractions of eastward flowing currents and winds blowing from the east are almost identical. The inescapable conclusion is that the current flow past the meter must be contrary to the wind direction for a substantial portion of the time.

In an attempt to find a possible explanation for this unexpected situation, an hour-by-hour plot of the wind and current was made in graphical form. The only definite relationship which it is possible to obtain from this plot is that a gale force wind from the southwest will cause an eastward flowing current at the meter site. Under all other wind directions and velocities, the current fluctuated between eastward and westward in an unpredictable manner. Currents often remained steady under shifting winds and just as often fluctuated while the wind remained steady.

There are several possible reasons for these apparently inconsistent results. The first possibility is that the current recording system might have malfunctioned. However, the individual switch-and-circuit nature of the instrument insures that the device either operates correctly or does not operate at all. There remains the possibility that the device was oriented incorrectly on the lake bottom thereby reporting eastward currents when they were flowing toward the west. This is rendered unlikely by the orientation checks made at the time of installation. The tripod alignment was checked both by diver's compass and by reference to the line of the cable extending from the meter to the light structure. Further, it was observed that the meter reported a strong eastward flowing current just prior to its being overturned during the gale of 26 September 1964. When it was recovered on 5 November 1964 the tripod was found to be overturned toward the east. Therefore, the meter must have been registering the correct current direction at the time it was overturned.

A second possibility is that the current at the meter site is typically stratified, with the surface current flowing in direct response to the wind and the bottom current representing a counter-flow. This condition does exist at the 1963 meter site on Sleeping Bear Shoal, which is quite near the shore. However the 1964 meter site is over 3 miles from the nearest point of land and in a very exposed position. Any condition of set-up and counter-flow would be unlikely. The shallow depth at the site precludes any significant thermal stratification during the late summer period of record. At no time during the entire summer and fall was a stratification

observed by divers, nor did they ever find the bottom current to be significantly different from the surface current.

If the two above possibilities are discounted it becomes necessary to assume that the current in Manitou Passage cannot be a simple through-flowing current which responds directly to the local winds, but must have a more complex interrelationship with the rest of Lake Michigan. This could manifest itself as the observed current pattern in either of two ways. The passage might have an unstable current regime with a complex of shifting gyrals causing repeated fluctuations of the current at any point. On the other hand, conditions might be such that the current at the North Manitou Shoal meter site flows northward or southward for a significant fraction of the time. The restricted direction-reporting ability of the meter would result in its reporting the full velocity of a north or south current but it would report whatever slight east or west component that current might have as a full indication of eastward or westward current. It will require a much more extensive survey of the current pattern of the Manitou Passage area before this problem can be resolved.

The tabulation of current velocities (table 4) is however, quite valid and indicates an extremely vigorous current regime. At this site, currents strong enough to erode and transport medium sand exist 80% of the time and currents powerful enough to erode silt, sand and fine gravel are attained 2% of the time.

Assumptions of the ability of a given current velocity to erode a sediment are based on the Threshold Mean Velocity curve of Hjulstrom as described by Inman (1963). This uses the mean current velocity measured 100 cm above the bottom. Since the height of the lower end

of the pendulum varies from about 20 cm to over 50 cm, this approximation will yield conservative estimates.

CONCLUSIONS

Despite the inability to describe the current pattern in Manitou Passage, it is evident that the near-bottom currents over the shoal areas and along the shoreline are often capable of actively eroding and transporting the sediments found in these areas. Moreover the land adjacent to these areas consists of a sandy moraine material which is very easily eroded (Kelley, 1957). During high water stages of Lake Michigan the bluff shorelines of the area, such as the west face of Sleeping Bear Hill are subject to direct wave attack and the vigorous alongshore currents certainly must be able to remove the material as fast as it is eroded. Gillis and Bakeman (1963) report that they measure a retreat of the crest of the bluff on the west face of Sleeping Bear Hill of 53 feet in 30 years (figs. 1 and 17). Since this slope is close to the angle of repose for this material the figure must indicate the retreat of the entire face of the hill. If the overall rate of retreat of the shoreline has been at about this rate, the hill must have extended over a mile farther into the lake at the beginning of the Nipissing stage.

About a mile southward from the tip of Sleeping Bear Point a layer of cobbles is found exposed in the face of the low hill which lies just inshore from the beach. The material above this layer is clean medium sand while below it is a reddish brown sand very similar to the material found under the cobble area at the center of Sleeping

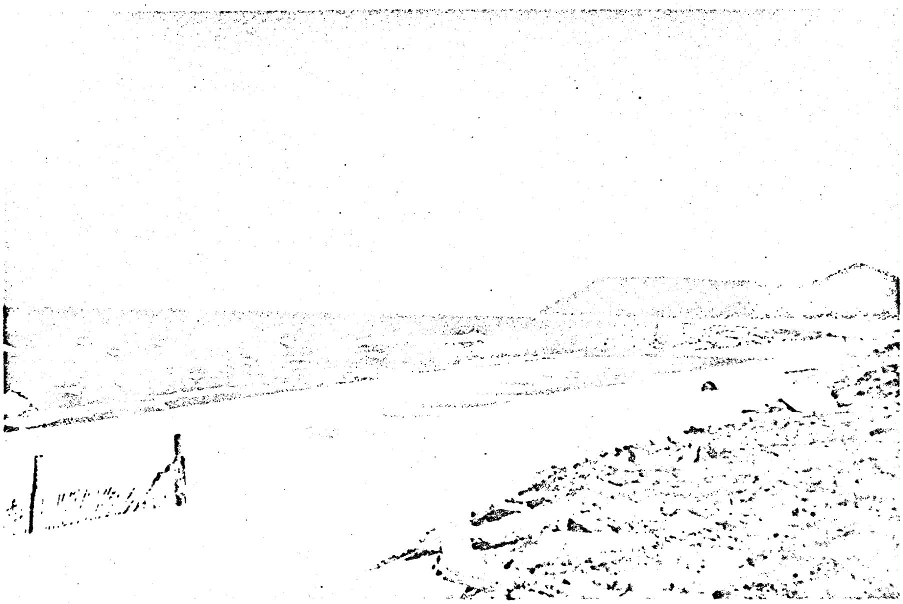

Figure 17 Profile of the west face of Sleeping Bear Hill

Bear Shoal. This layer is about 10 feet above the present lake level which means that it would have been at a depth of 15 feet during the Nipissing stage and could well have been an offshore cobble pavement area similar to those found on the shoal areas now and that it has been subsequently covered by beach or dune sand. This implies a major outbuilding of Sleeping Bear Point in the last 4,000 years.

The above mentioned retreat of the face of Sleeping Bear Hill permits another estimate of the approximate intensity of the sedimentary activity of the area. If this 50 foot retreat of the slope is assumed to apply to the whole length of the west face of the hill (about 10,000 feet) this would imply the removal of some 150,000,000 cubic feet of material in the 30 year period. If only half this material were carried around, or blown over, Sleeping Bear Point, it would be enough to cover the western half of Sleeping Bear Bay with a layer about a foot thick. This agrees quite well with the previous estimate of 2-3 feet per century.

Considering the demonstrated vigor of the geological processes at work in the Manitou Passage area, it becomes possible to make an estimate of the recent geomorphic history of the area as follows.

Sleeping Bear Hill once extended over much of the present area of Sleeping Bear Shoal. The hill has been cut back by wind and water action and its material transported northward. Much of this material has gone to form Sleeping Bear Point with its numerous sand dunes. The rest of the sand has been carried around Sleeping Bear Point to fill part of Sleeping Bear Bay and isolate the present Glen Lake from Lake Michigan (Johnson, 1958).

South Manitou Island is being moved eastward, the western side being eroded, and transport of sand around both the north and south sides of the island is constructing the opposing points which enclose the natural harbor on the east side of the island.

Much of the southern end of North Manitou Island has been removed and its material may have been dropped into the deep area to the east of the island. In a similar manner the tip of Pyramid Point has been removed.

The central basin has remained a body of water throughout post-glacial time and is at present receiving the silt fraction of the eroded sediments over its entire extent while being encroached upon by the advancing Sleeping Bear and South Manitou Shoals.

Owing to the extreme rapidity of geomorphic evolution in Manitou Passage, the area affords an excellent opportunity for the observation and study of the processes of erosion and deposition in the near-shore and offshore environments. Further extensive and intensive study of the area should yield knowledge applicable to much of the remainder of the Great Lakes.

APPENDIX

Mechanical composition of sediment samples
(Locations are shown in figure 9)

Sample No.	Phi Measures Median	Mean	Deviation	Skewness[1]
000	1.8	1.8	0.4	
001	2.8	2.8	1.2	
002	3.1	3.2	1.8	.06
003	1.9	2.8	1.4	.64
004	2.0	2.8	1.4	.57
005	2.0	2.8	1.4	.57
006	3.1	2.9	1.0	-.20
007	2.0	2.1	0.6	.17
008	1.1	1.1	0.6	
009	1.7	1.8	0.5	.20
010	2.2	2.2	0.6	
011	1.7	1.8	0.6	.17
012	2.2	2.8	1.4	.43
013	2.7	2.6	0.8	-.13
014	1.7	1.7	0.4	
015	1.8	1.9	0.5	.20
016	2.3	2.3	0.6	
017	2.0	2.1	0.5	.20
018	Pebbles and small cobbles			
019	Small cobbles			
020	1.5	1.4	0.4	-.25
021	1.5	1.5	0.5	
022	1.8	1.8	0.4	
023	1.9	2.0	0.4	-.25
024	1.6	1.6	0.3	
025	1.8	1.9	0.4	.25
026	2.5	2.4	0.6	-.17
027	1.8	1.9	0.4	.25
028	2.4	2.4	0.7	
029	3.4	3.2	1.7	-.12
030	3.1	3.4	0.6	.50
031	3.0	3.2	0.8	.25
032	1.7	1.8	1.0	.10

Sample No.	Phi Measures			
	Median	Mean	Deviation	Skewness$_1$
100	1.6	1.6	0.3	
101	2.1	3.1	1.8	.56
102	5.4	3.8	2.0	-.80
103	5.8	4.9	1.4	-.64
105	1.8	2.7	1.4	.36
106	2.5	2.7	1.4	.14
107	Small pebbles			
108	1.5	2.1	1.2	.50
109	2.0	2.9	1.6	.56
110	Cobbles			
111	3.6	3.7	2.2	.05
112	2.9	3.5	2.2	.27
113	2.0	2.7	1.5	.47
114	1.9	2.1	0.7	.29
150	1.7	2.0	0.7	.43
151	1.8	2.0	0.7	.29
152	1.8	2.6	1.3	.62
153	5.2	4.2	1.8	-.56
154	5.8	4.6	1.9	-.63
155	5.4	3.9	1.8	-.83
156	2.9	2.9	1.3	
157	3.5	3.5	2.0	
160	1.3	1.3	0.5	